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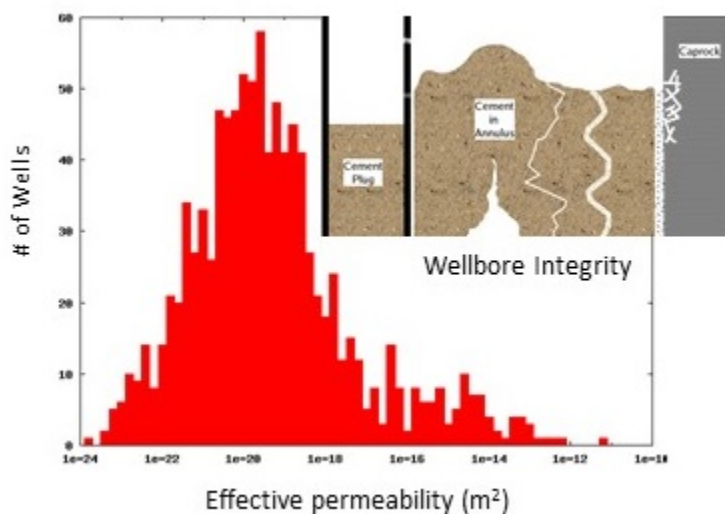
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Probability Distributions for Effective Permeability of Potentially Leaking Wells at CO₂ Sequestration Sites

21 April 2017



U.S. DEPARTMENT OF
ENERGY



Office of Fossil Energy

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Cover Illustration: A probability distribution of permeability of wells at a hypothetical sequestration site with 1,000 older wells. The wells range from very secure (permeability $< 10^{-18} \text{ m}^2$), to very minor leakage ($< 10^{-16} \text{ m}^2$), to measurable leakage ($> 10^{-16} \text{ m}^2$), to significant leakage ($> 10^{-12} \text{ m}^2$). The total permeability of the wells is equivalent to 10 D (Darcy), which is dominated by a single defective well. The inset shows a closeup view of leakage pathways in a wellbore system consisting of steel casing, a cement plug, a partially cement-filled annulus and caprock.

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Probability Distributions for Effective Permeability of Potentially Leaking Wells at CO₂ Sequestration Sites

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Acronyms, Abbreviations, and Symbols

Term	Description
CO ₂	Carbon dioxide
IEA	International Energy Agency
NRAP	National Risk Assessment Partnership
O&G	Oil and gas
SCP	Sustained casing pressure
SCVF	Surface casing vent flow

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EXECUTIVE SUMMARY

Wells with defects originating from either poor completions or subsequent damage arising from chemical, thermal and/or mechanical stresses provide potential pathways for leakage of carbon dioxide (CO₂) and brine from a CO₂ sequestration site. This report provides a methodology for analyzing data on the frequency of occurrence of defective wells and the effective permeability of the damaged wells. The results include bimodal, log-normal distributions of the effective permeability of wells in addition to other distributions designed to provide a measure of the likelihood of encountering a leaking well in a CO₂ storage project. The existing data are rather sparse for constructing these distributions and significant improvements are possible through further studies of the field performance of wells. Such studies would result in refinements to the permeability distributions presented here. The existing data include those reported in a risk assessment report by the FutureGen project (FutureGen, 2007) and those from studies of sustained casing pressure by Bourgoyne et al. (2000), Watson and Bachu (2007), and Tao et al. (2010a). A conceptual model is used in which the external, cement-filled annulus of wells is regarded as having a finite permeability, which in most wells is sufficiently low such that leakage is both undetectable and insignificant. The results show that potential impacts to CO₂ sequestration project performance are driven by a few defective wells.

1. INTRODUCTION

The National Risk Assessment Partnership's (NRAP) approach to quantifying risk of wellbore leakage during geologic sequestration of carbon dioxide (CO₂) considers the potential from project-installed wells in addition to existing wells within the area of influence. NRAP uses several approaches to characterize the leakage potential of cemented and open wells including a method based on estimated representative range and distribution of wellbore effective permeability. In this study, published and unpublished research on sustained casing pressure (also known as surface casing vent flow) is used as a basis to develop a probability distribution for permeability external to the casing for older, existing wells within a sequestration project area. The objective is to use these probability distributions to calculate the likelihood and severity of leakage of CO₂ or brine to shallow aquifers or the atmosphere.

CO₂ and/or brine leakage poses one of the most significant risks to permanent sequestration of CO₂ (Metz et al., 2005). Potential impacts of leakage include loss of CO₂ from the storage complex, harm to the environment (as emissions to the atmosphere or infiltration into groundwater), harm to human health, and loss of carbon credits. This report focuses on leakage through the external annulus of existing (older) wells within the area of concern of the sequestration project (Figure 1). The external annulus is outside the casing and is filled with cement or residual drilling fluid. Leakage through the external annulus can occur through a number of wellbore defects including fractures in cement and flow along interfaces between the cement and the caprock (see pathways #3 to #8 in Figure 1). This study does not consider open-hole flow inside the casing. This has been addressed in other research activities of NRAP's Well and Seal Working Group (Pan et al., 2011). Internal wellbore leakage is not readily characterized as an effective permeability and involves much higher flow rates, although it is much rarer in occurrence.

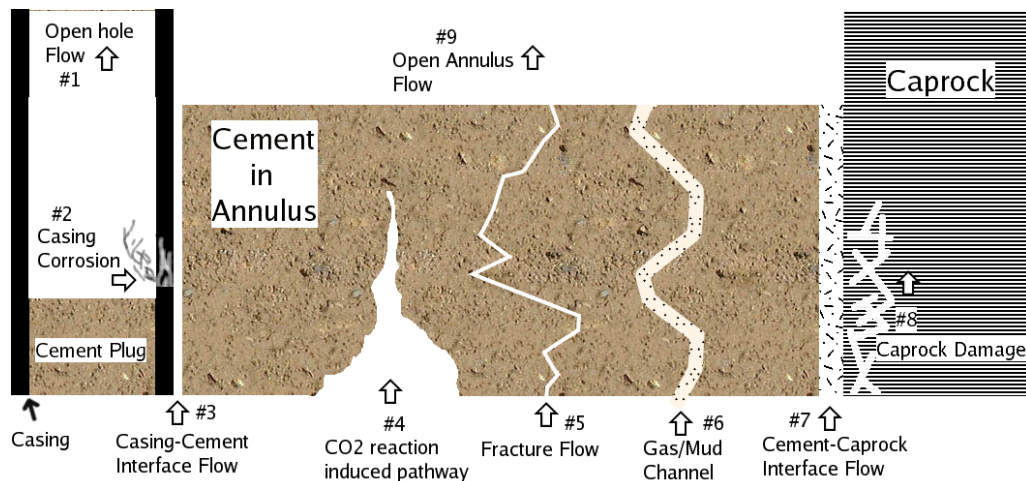


Figure 1: Schematic diagram illustrating potential leakage pathways in an abandoned well. Modified from Viswanathan et al. (2008).

There is very little information available providing either estimates of the frequency with which leaks occur in external annuli or the effective permeability of these leaks. This report uses two sources of information to provide these estimates. The first is the results of a detailed risk

analysis conducted by the FutureGen project (FutureGen, 2007), which derived some useful wellbore failure frequencies. The FutureGen report was based in large measure on failure frequencies observed in natural gas storage facilities as summarized in a study sponsored by the International Energy Agency (IEA) Greenhouse Gas Programme (IEA, 2006) and summarized in Papanikolaou et al. (2006).

The second source is observations of sustained casing pressure (SCP), see Figure 2 (Bourgoyne et al., 2000; Watson and Bachu, 2007; Tao et al., 2010b, 2011). These are observations of gas leakage occurring within one or more *internal* annuli of a well (Figure 3) and are monitored by pressure gauges or vent lines on the annuli. While these are good analogs for some leakage mechanisms, SCP includes a variety of phenomena that would not be expected to be important pathways in CO₂ sequestration including: leaks in tubing joints that occur between production tubing and production casing, and intrusion of shallow gas into uncemented regions of the well such as below the surface casing and above the top of cement for the production casing. In many cases, the cause of the gas leak may be unknown so that SCP statistics must be applied with care. Further, SCP statistics generally do not include gas migration in the external annulus as this leaks outside of the well into the region surrounding the well. Nonetheless, SCP provides the best available analog with significant statistics for evaluating the potential for leaking wells.



Figure 2: Photographs of gas leakage (methane) due to sustained casing pressure in abandoned wells from Alberta, Canada (from Watson and Bachu, 2007).

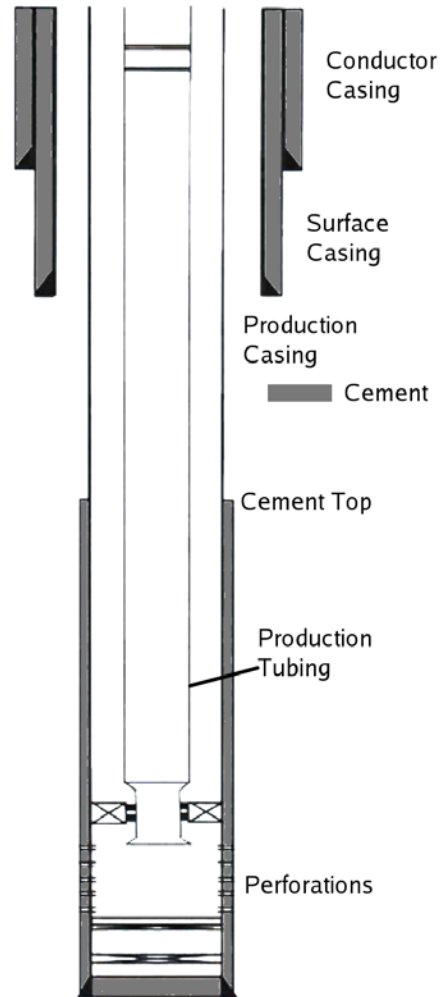


Figure 3: Schematic diagram of an operating production well showing key casing elements and location of cement. Sustained casing pressure can occur between any of the casing elements such as production tubing-casing or surface-conductor casing.

There are several approaches to representing wellbore leakage risk. The FutureGen project (FutureGen, 2007) developed risk as the probability that a single well will leak at a discrete high or low rate given as mass of CO₂ released per unit time. This is an “either-or” approach in which a well either leaks or provides a perfect seal. This also simplifies the physics of the problem by assuming a constant flow rate, whereas in reality flow rate will be governed by permeability of the leakage path and pressure gradient and fluid saturation conditions within the CO₂ storage reservoir. A second approach used in this report treats all wells as imperfect barriers to gas migration with a range of effective permeabilities that result in fluid leakage ranging from imperceptible and insignificant to measurable and impactful. In the first approach, a project with a few wells may conclude that with high probability there will be zero leakage from wells. In the second approach, a project with a few wells would not estimate zero leakage but would conclude that there would likely be insignificant leakage. The end result is similar, but it is difficult to argue that wells have “zero leakage” because it is well known that the material used to create

isolation in wellbore systems (Portland cement) has a finite permeability and because the effective permeability of wells is likely to be a continuum of values rather than discrete zero or non-zero permeabilities. This report uses the second approach, although in the analysis of SCP cases it assumes that wells without gas leakage have a constant low permeability rather than a distribution of permeabilities.

2. METHODOLOGY

2.1 DEVELOPMENT OF A FREQUENCY DISTRIBUTION

This study assumes that wells have a log-normal distribution of permeabilities. This creates a distribution of permeabilities weighted toward low values so that the resulting frequencies predict that the majority of wells have low permeabilities with a few high-permeability outliers (leaking wells). Conveniently, this is a normal distribution of permeabilities in log-permeability space. An expression for a log-normal distribution is as follows:

$$\text{frequency of permeability, } f(k) = \frac{1}{k\sigma\sqrt{2\pi}} 10^{\left(\frac{-(\log(k)+\mu)^2}{2\sigma^2}\right)} \quad (1)$$

here k is the permeability, μ is the mean of the log (base 10) values of the permeability and σ is the corresponding standard deviation. The mean value of permeability in real values (not in terms of logarithms) is

$$\text{mean permeability, } 10^{\left(\mu + \frac{\sigma^2}{2}\right)} \quad (2)$$

This study treats each well as contributing its own permeability, k_i , so that the total permeability of the wells in the field is given by the sum, Σk_i , assuming that all wells have the same cross-sectional area.

2.2 PROBABILITY DISTRIBUTION ESTIMATED FROM FUTUREGEN

The FutureGen project created a risk assessment framework for leaking wells in terms of well failures per year, per well (FutureGen, 2007). The project distinguished between three classes of wells: CO₂ wells, oil and gas (O&G) wells, and undocumented wells. The project further distinguished between two types of leakage events: a low-rate leak of 200 metric tonnes/year and a high-rate event of 11,000 metric tonnes/year. These were estimated to occur once in 10⁻³ to 10⁻⁵ well-years. High-leak rate events were assumed to be discovered and remediated within a relatively short period of time (0.01 years). Low leak rate events were assumed to be essentially undetectable. A summary of the FutureGen risk calculations is given in Table 1.

Table 1: Failure rates for wells used in the FutureGen report (FutureGen, 2007)

Type of well	Leak Rate	Frequency (per year-well)	Rate (tonne/yr)	Duration (yr)
Deep CO ₂ wells	high rate	1.E-05	11,000	0.01
Deep CO ₂ wells	low rate	1.E-05	200	5,000
Deep O&G wells	high rate	1.E-03	11,000	0.1
Deep O&G wells	low rate	1.E-03	200	5,000
Undocumented deep wells	high rate	1.E-03	500	0.01
Undocumented deep wells	low rate	1.E-03	200	5,000

2.2.1 Calculation of Permeabilities from FutureGen Results

The FutureGen well-failure analysis provides a useful starting point for NRAP, however, this approach requires permeabilities rather than failure events. The FutureGen results can be transformed into permeabilities with a few assumptions as follows.

FutureGen (Table 1) gives leakage rates. By making assumptions about the pressure drive for leakage (ΔP), the length of the leakage path (L), and the area of the leaking wellbore (A), an effective permeability can be derived from the following equation:

$$Q = \frac{kA\Delta P}{\mu L} \quad (3)$$

where Q is the leak rate supplied by FutureGen. Permeability can be related to an equivalent aperture derived from the cubic equation for flow through a parallel plate. This relationship is:

$$k = \frac{b^2}{12} \quad (4)$$

Where b is the equivalent fracture aperture. Table 2 illustrates some example calculations that indicate effective wellbore permeabilities are on the order of 10 Darcy (D) for the low leakage rate and 500 D for the high leakage rate.

Table 2: Values from example calculation to convert leak rate in metric tonnes given by the FutureGen report (Table 1; FutureGen, 2007) to an equivalent wellbore permeability using Equations 3 and 4

Parameter	Low Rate	High Rate
CO ₂ leak rate (tonnes/year)	200	11,000
CO ₂ density (g/cm ³)	0.6	0.6
CO ₂ leak rate (m ³ /year)	333.33	18333.33
CO ₂ leak rate (Q ; m ³ /sec)	1.06E-05	5.81E-04
Exterior well radius (in)	7	7
Interior well radius (in)	5	5
Area (A ; m ²)	0.0486	0.0486
Pressure (ΔP ; bar)	100	100
Pressure (ΔP ; Pa)	1.00E+07	1.00E+07
Length (L ; m)	4,000	4,000
Viscosity (μ ; Pa-s)	1.00E-04	1.00E-04
Permeability (k ; m ²)	8.69E-12	4.78E-10
Permeability (Darcy)	8.69	477.72
Equivalent fracture (μm) (Equation 4)	209	794

The risk analysis strategy requires a frequency distribution of permeabilities. For the low leak rate case, the FutureGen report suggests that 1 in 1,000 non-CO₂ wells or 1 in 100,000 CO₂ wells will have a permeability of about 10 D. One approach to achieving this with a probability distribution is to design the distribution to generate a total permeability across all of the wells of 10 D for either 1,000 or 100,000 wells.

For the 1 in 1,000 event, choosing $\mu = -16$ and $\sigma^2 = 2$ in Equation 1 generates a distribution with a mean log permeability equivalent to 1 mD (milliDarcy^{*}). The sum of 1,000 such samples turns out to have a net permeability of about 10 D (Darcy[†]). The net permeability was calculated as follows:

1. Generate 1,000 random values from a normal distribution with mean of 0 and standard deviation of 1
2. Create permeabilities with the formula $k_i = 10^{\mu + \sigma N_i}$ where N_i are the normal distribution values from the first step
3. Form the sum Σk_i of all permeabilities to determine the net permeability of the 1,000 wells

A series of 10 calculations of 1,000 samples generated net permeabilities (Darcy) of 15.7, 9.1, 33.5, 21.8, 7.0, 18.8, 14.7, 6.8, 13.0, and 4.9. An example histogram of a calculation is given in Figure 4. The 1 in 100,000 distribution can be obtained similarly using $\mu = -18$.

^{*} 1 milliDarcy = 10^{-15} m²

[†] 1 Darcy = 10^{-12} m²

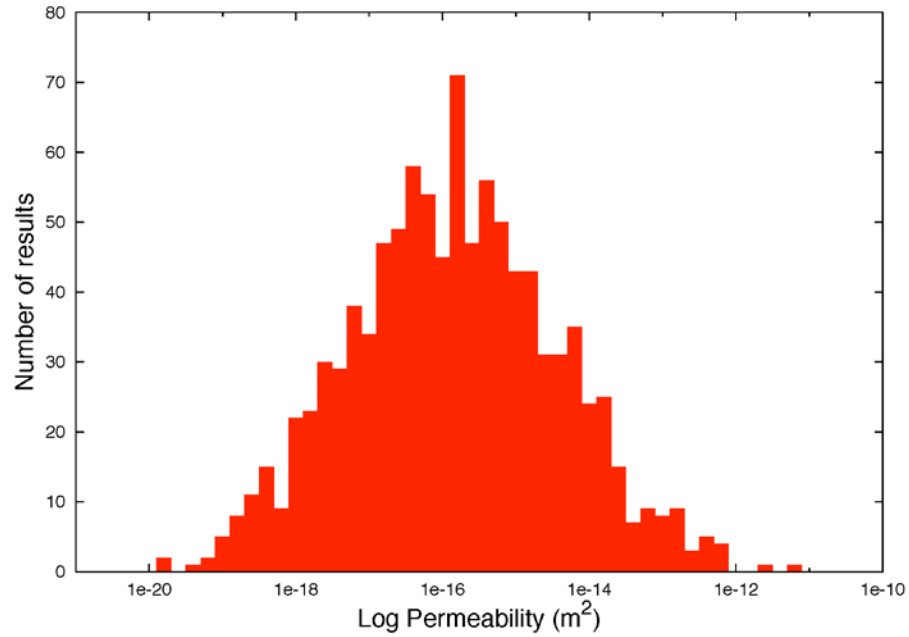


Figure 4: Histogram of 1,000 samples from a log-normal distribution with mean -16 and variance 2. The total permeability is dominated by the few high-permeability values and is equal to about 10 D.

There are an infinite number of frequency distributions that will reproduce the desired net permeability. An example bi-modal, log-normal distribution that accomplishes this is illustrated in Figure 5, which was created with 10% of the sample corresponding to a mean of -15 and variance of 2 and 90% of the sample corresponding to a mean of -20 and variance of 2. The net permeability of this particular realization is 5.9 D.

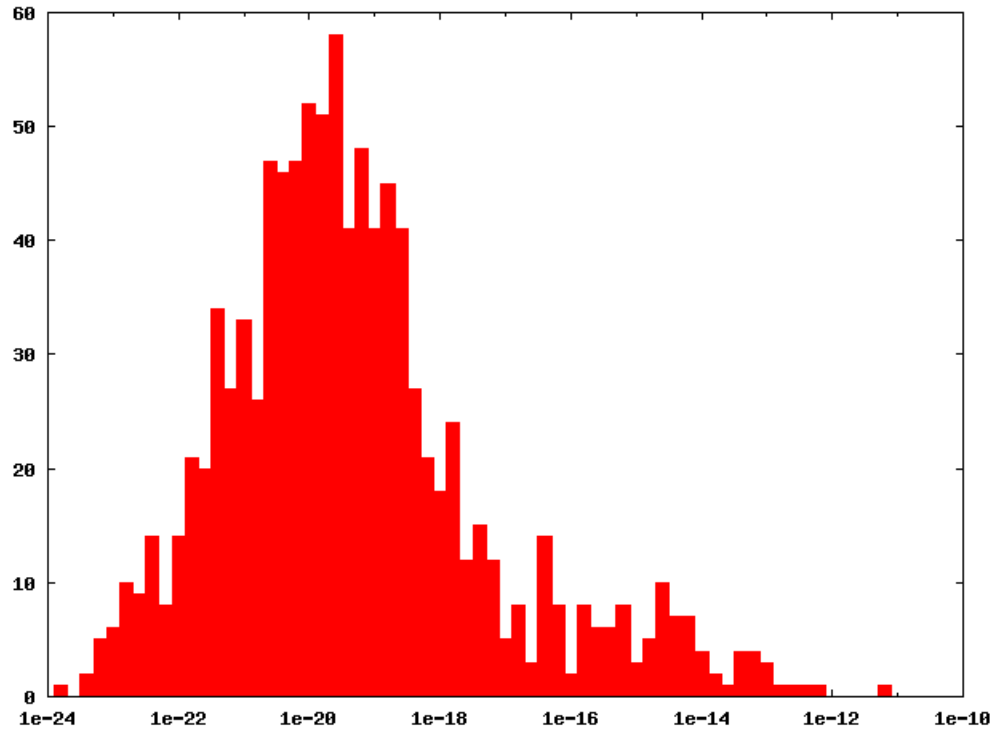


Figure 5: Histogram of 1,000 samples from a bimodal log-normal distribution created by summing 10% of one distribution with mean -15 and variance 2, and 90% of another distribution with mean -20 and variance 2. The net permeability is dominated by one high-permeability value (69%).

2.3 SUSTAINED CASING PRESSURE DATA FOR OFFSHORE WELLS IN THE GULF OF MEXICO

Sustained casing pressure data from the Gulf of Mexico were summarized in a report by Bourgoynne et al. (2000) with further analysis of effective permeability in Tao et al. (2010a,b, 2011). Gulf of Mexico wells should not be viewed as representative of onshore wells as they are offshore, developed in rather unconsolidated sediments, and subject to numerous shallow gas zones above the target reservoirs. All of these factors make them more prone to developing sustained casing pressure and thus represent a worse-case scenario for onshore leakage. As discussed by Bourgoynne et al. (2000), SCP can be a serious problem and existing regulations require remediation where significant pressure build-up occurs. In worst case scenarios, SCP can lead to sufficiently high pressures within the casing string that the outer casing bursts resulting in blowouts to shallow formations or the subsea.

The problem of SCP is widespread in the Gulf of Mexico. Bourgoynne et al. (2000) identified more than 8,000 wells in the Gulf of Mexico with SCP, and of these, about 50% of SCP were related to production tubing leaks. These are not relevant to considerations in CO₂ sequestration in which the main concern is abandoned wells that are no longer producing and generally do not have production tubing. By analysis of Figure 3.2 in Bourgoynne et al. (2000), this study found that the average percentage of wells with non-production related SCP on a per-field basis was 11.4%, while 11.5% of all wells in the Gulf of Mexico had non-production related SCP. The

range of observed SCP rates was between 2–29% of wells in a field. Bourgoyne et al. (2000) found that about a 1/3 of the SCP are in operating wells; 2/3 are in shut-in or temporarily abandoned wells (the performance of plugged and abandoned wells was not considered).

Xu and Wojtanowicz (2001) further analyzed 26 wells from a single field in the Gulf of Mexico and found that 85% of the wells had SCP. Of these, 30% of the cases related to production casing and therefore were not relevant to the sequestration scenario. They further developed a simple analytical formula for calculating mass flow based on observations of SCP. They studied two wells in detail and found rather low effective permeabilities of 0.001 and 0.003 mD (cf., Table 2 and the FutureGen calculations).

Tao et al. (2010a,b, 2011) evaluated the Gulf of Mexico SCP data in detail for 20 wells. They calculated effective permeabilities that ranged from 0.01–100 mD for 20 leaking wells shown in Figure 6. These values were obtained by modeling the rate of the observed annular pressure build-up as due to migration of gas from the reservoir through the defective cement column and through the overlying mud column. A range of values was obtained because of uncertainties in the depth of the leak and the length of the mud column through which the gas migrated. They calculated that 19 of the 20 wells have effective permeabilities of less than about 1 mD. One of the wells has an effective permeability much closer to 100 mD. The expected flux follows a similar pattern (Figure 7). Note that the maximum flux corresponds to about 15 tonnes of CO₂/year. The effective permeabilities of the limited number of cases examined were characterized by a log normal distribution.

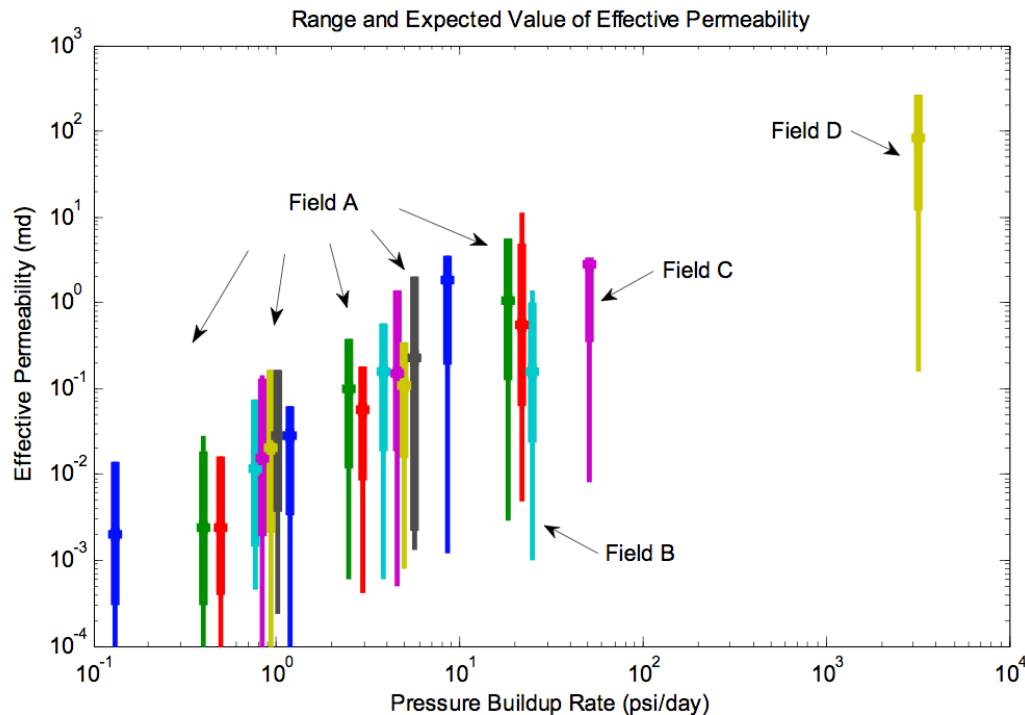


Figure 6: Range and most probable values of permeability calculated by Tao et al. (2010a) for 20 wells from four fields in the Gulf of Mexico (from Tao et al., 2010a).

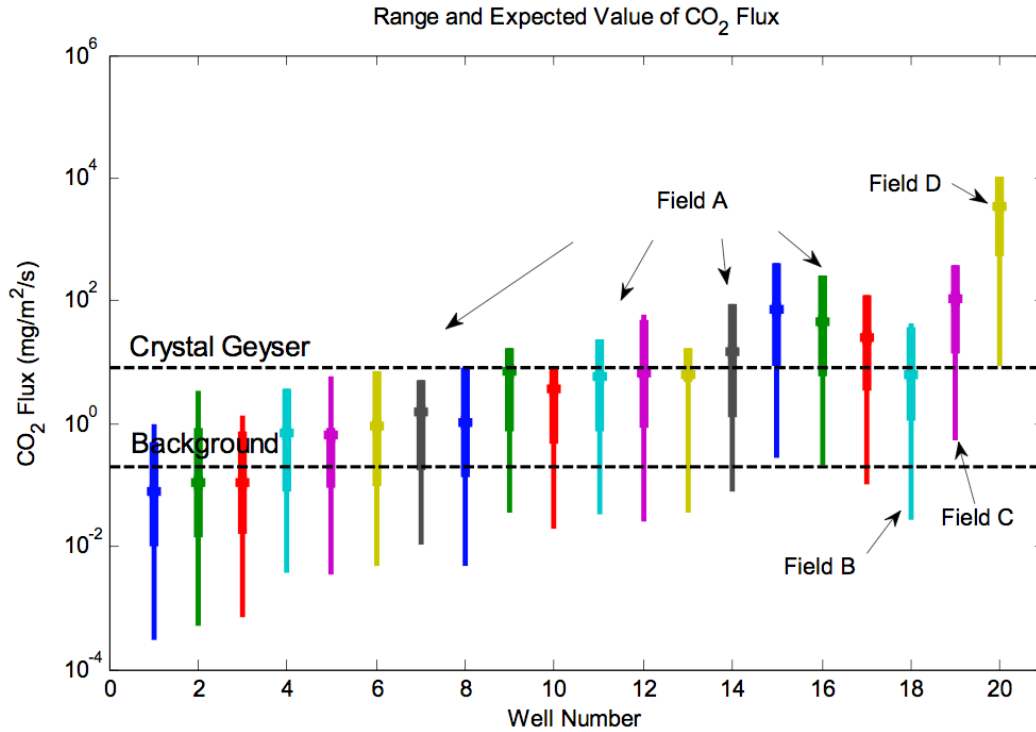


Figure 7: Range of equivalent CO₂ flux calculated by Tao et al. (2010a) for 20 wells with sustained casing pressure in the Gulf of Mexico. The rank-ordered values illustrate the approximate magnitude of CO₂ leakage that would be expected from wells that leak with effective permeabilities observed in the Gulf of Mexico (Figure 6) (from Tao et al., 2010a).

2.4 SUSTAINED CASING PRESSURE FOR ONSHORE WELLS IN ALBERTA

Watson and Bachu (2007, 2008) studied the occurrence of sustained casing pressure (called surface casing vent flow, SCVF, in Canada) in the province of Alberta through the use of regulatory agency records. Their survey included about 316,000 wells. They developed several notable conclusions. Wells that were drilled and abandoned (i.e., they were not completed and do not have casing) have very low probability of measurable SCP ($< 0.5\%$). In contrast, abandoned cased wells had a much higher rate of SCP at 14%, greater than the rates observed in the Gulf of Mexico (11.5%). Combining these two well types, the overall rate of SCP for Alberta was 4.6%. Watson and Bachu also obtained records for gas migration, which were events in which gas leakage was found in soils or other areas removed from the well itself. Gas migration involves the same failure mechanism as SCP, but the gas escapes the well annuli and migrates into the surrounding soil. Watson and Bachu found that 13% of the total SCP problems also involved gas migration. These statistics may be more relevant to the sequestration environment, but the following analysis used the more conservative 4.6% rate.

Watson and Bachu (2007) also found that the occurrence of SCP did not correlate with temporal factors (age or length of operation), but found that one key correlation was the length of uncemented steel casing. Other important factors included the geographical region (some areas within Alberta were more prone to SCP), well deviation (non-vertical wells were more prone to

SCP), and the amount of drilling activity (presumably high-demand environments resulted in less careful well completions that were more likely to develop SCP).

Note: A recent report by Zhu et al. (2012) discusses SCP in China, but it was not used in developing the model in this report. In that study, Zhu et al. examined 13 wells, 12 of which had SCP, and reported an effective permeability of 18 mD on one well.

3. DEVELOPMENT OF PERMEABILITY DISTRIBUTIONS

The following sources of information have been used for developing permeability distributions:

1. FutureGen (2007): review of natural gas and Australian risk programs. Provides failures as mass flow rate on a per well-year basis
2. Watson and Bachu (2007): review of sustained casing pressure in Alberta, Canada and contains frequency of failures but without leak rate
3. Tao et al. (2010b): uses sustained casing pressure data in Gulf of Mexico to determine permeability and provides leak rates but not frequency of failure
4. Bourgoyne et al. (2000); Xu and Wojtanowicz (2001): review of sustained casing pressure in the Gulf of Mexico provides frequency and two calculations of permeability

Using the approach described in Section 2, six different bi-modal, log-normal probability distributions were created using Equations 1 and 2. The FutureGen report (Table 1) was used to generate four of these cases, each consisting of a log-normal population of slowly to negligibly leaking wells and a log-normal population of more rapidly leaking wells. These calculations assumed that 90% of the wells were performing adequately and 10% had larger magnitude permeability. For all four cases, the sum of the population of wells was designed so that the net leak rate corresponded to the FutureGen scenario listed in Table 1.

The probability distributions for sustained casing pressure data were treated somewhat differently to illustrate an alternative approach. For both the Gulf of Mexico and Alberta cases, the wells were divided into three populations, one of which had a constant, negligible permeability and two of which had a relatively high permeability drawn from a uniform distribution corresponding to the calculations of Tao et al. (2010a). The Gulf of Mexico and Alberta cases differed only in the fraction of wells divided between the high and low permeability populations.

The six probability distributions are summarized as follows:

1. FutureGen Case 1: low flow rate with frequency 1 in 1,000 well-years
 - a) 10% of a log-normal distribution with mean 10^{-15} m^2 and standard deviation 2
 - b) 90% of a log-normal distribution with mean 10^{-20} m^2 and standard deviation 2
 - c) Figure 8
2. FutureGen Case 2: low flow rate with frequency 1 in 100,000 well-years
 - a) 10% of a log-normal distribution with mean 10^{-17} m^2 and standard deviation 2
 - b) 90% of a log-normal distribution with mean 10^{-20} m^2 and standard deviation 2
 - c) (not illustrated)
3. FutureGen Case 3: high flow rate with frequency 1 in 1,000 well-years
 - a) 10% of a log-normal distribution with mean 10^{-13} m^2 and standard deviation 2
 - b) 90% of a log-normal distribution with mean 10^{-20} m^2 and standard deviation 2
 - c) (not illustrated)

4. FutureGen Case 4: high flow rate with frequency 1 in 100,000 well-years
 - a) 10% of a log-normal distribution with mean 10^{-15} m^2 and standard deviation 1.5
 - b) 90% of a log-normal distribution with mean 10^{-18} m^2 and standard deviation 1
 - c) Figure 9
5. Gulf of Mexico Case 5
 - a) 88% of wells do not have observable SCP and were assigned a negligible permeability of 10^{-20} m^2
 - b) 11.4% of wells are slow leakers and were assigned a permeability from a uniform distribution between 10^{-17} and 10^{-14} m^2
 - c) 0.6% of wells are fast leakers and were assigned a permeability from a uniform distribution between 10^{-13} and 10^{-12} m^2
 - d) Figure 10
6. Alberta Case 6
 - a) 95.4% of wells did not have SCP and were assigned a negligible permeability of 10^{-20} m^2
 - b) 4.4% of wells were slow leakers and were assigned a permeability from a uniform distribution between 10^{-17} and 10^{-14} m^2
 - c) 0.2% of wells were fast leakers and were assigned a permeability from a uniform distribution between 10^{-13} and 10^{-12} m^2
 - d) Figure 11

4. DISCUSSION

The six different probability distributions illustrated in Figures 8–11 provide a range of scenarios characterizing the distribution of permeability of older or existing wells within a sequestration domain. These distributions must be treated as highly uncertain as there are no direct measurements of total gas migration frequency and rates from any field situation. The FutureGen scenarios are based on analysis of the frequency and potential severity of actual well failures in analog natural gas storage facilities. This has the advantage of referring to discrete events with the potential for relatively large impact. The sustained casing pressure data, on the other hand, represent a more complete picture of the likelihood that any well has measurable gas migration. The disadvantage of the SCP data is that larger events or gas migration outside of the casing annuli are not well represented (see Watson and Bachu, 2007).

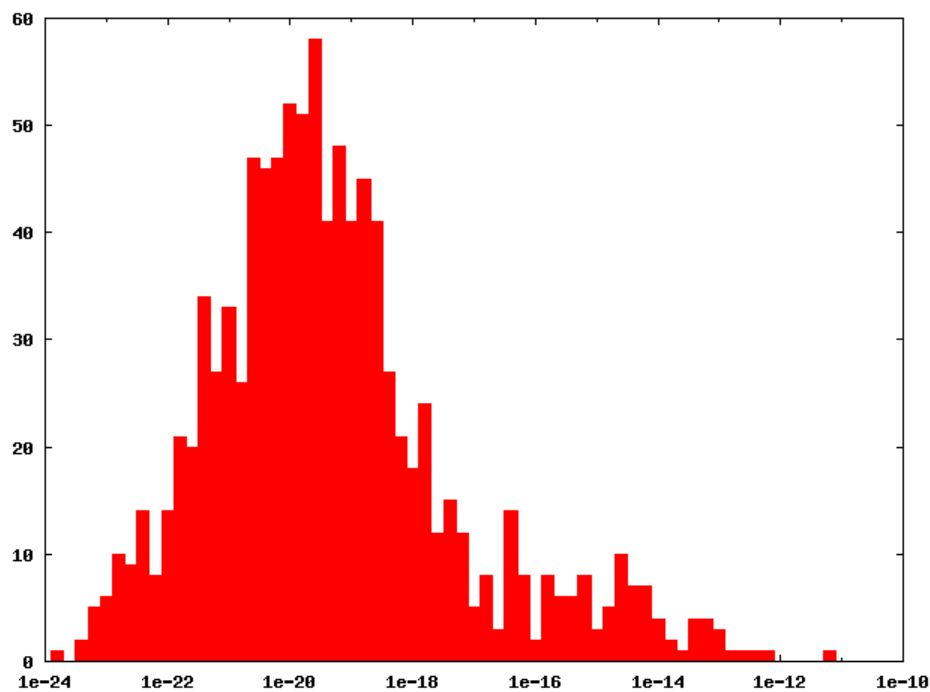


Figure 8: Histogram of effective permeability of 1,000 wells with a probability of leakage corresponding to FutureGen's 1 in 1,000 well-years leaking at 200 tonnes/yr.

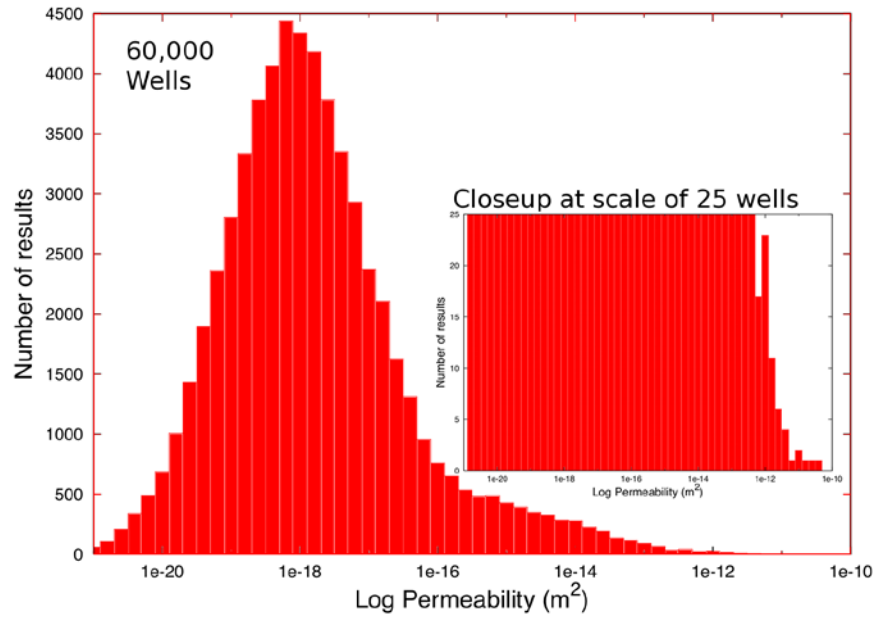


Figure 9: Histogram of effective permeability of 60,000 realizations with a probability of leakage corresponding to FutureGen's 1 in 100,000 well-years leaking at 11,000 tonnes/yr.

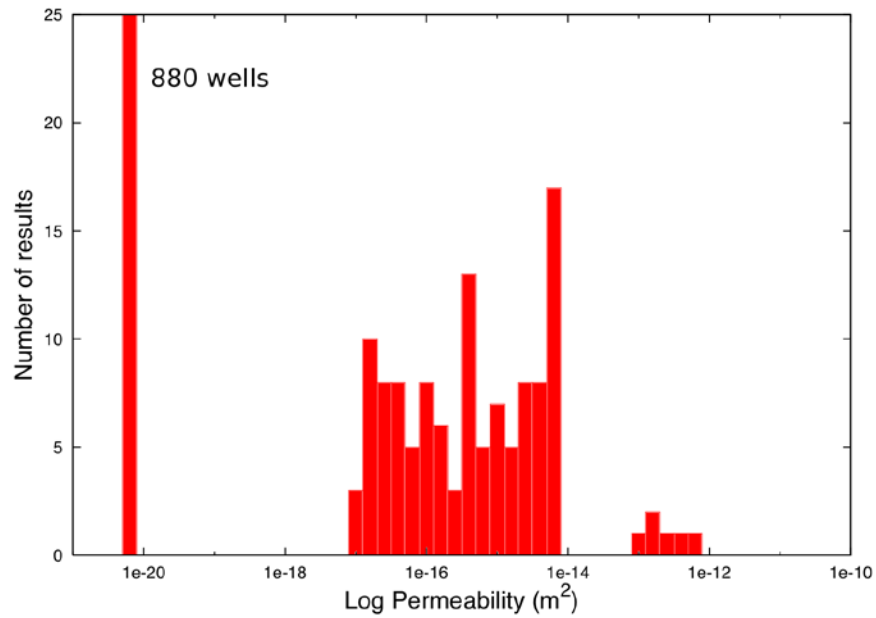


Figure 10: Histogram of effective permeability of 1,000 realizations with a probability of leakage corresponding to Gulf of Mexico frequency of SCP and calculated leak rates.

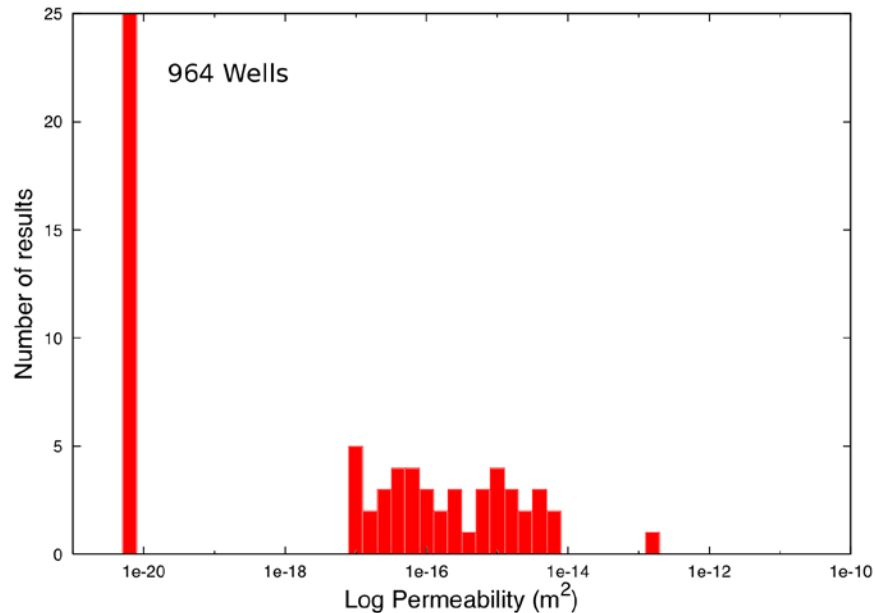


Figure 11: Histogram of effective permeability of 1,000 realizations with a probability of leakage corresponding to Alberta frequency of SCP with calculated leak rates from the Gulf of Mexico.

The differing probability distributions reflect distinct but perhaps subtle differences in conceptual models of potential CO₂ leakage at sequestration sites. The FutureGen risk assessment was cast in terms of events per well-year. This has the advantage of recognizing that it is more likely that a specific well will be the source of the most significant challenges to a sequestration project. The disadvantage is that the probabilities of a single well creating problems are sufficiently low that projects may conclude that there is no significant chance of leakage where there are relatively few potentially leaking wells. This does not recognize that all wells are likely to have some degree of gas migration (perhaps unmeasurable) and may lead to an unrealistic expectation of “zero leakage”.

The bi-modal log normal distributions developed to replicate the FutureGen scenarios in Cases 1–4 reflect a conceptual model in which all wells are imperfect and are leaking gas at rates ranging from negligible to significant amounts. In this view, wells exist in a broad spectrum of conditions leading to a wide range of effective permeabilities. Note that despite the range of permeability values in Figures 8–9, it is only the few highest permeability wells that contribute significantly to leakage risk.

The tri-modal constant and uniform distributions used to characterize permeabilities in Cases 5 and 6 represent a third view. In this approach, wells are classified into good and poor performing populations. The good performers have similar properties and a vanishingly small effective permeability. There is no range in their properties. The poor performers are a distinct population with much higher effective permeability including a distinct population that may be characterized as presenting severe problems.

The permeability distribution approach provides a practical method of calculating leakage rates from older wells within a CO₂ sequestration project area of influence. Rather than assuming that most wells are “perfect” and that leakage can only come from a rare, defective well, the approach used here reflects a realistic distribution of permeabilities acknowledging that all wells have a finite permeability. By using a range of permeabilities, sites with few wells can be analyzed for leakage magnitude without the awkward solution of concluding that a small number of wells are likely to be perfect and therefore the project has no leakage risk. By using permeabilities, this approach also connects naturally with reservoir simulations and allows full computational calculations of leakage as a function of reservoir conditions (pressure, saturation, time) rather than imposing arbitrary, constant leak rates. This approach allows treatment of both CO₂ and brine leakage with the same permeability formalism.

In viewing these permeability distributions, the question arises as to what the threshold is for significant leakage impacts to a sequestration project. This is an area of on-going research within NRAP and depends on complicated interactions of CO₂ with the engineered geologic system. However, the potential impacts associated with loss of CO₂ storage credits is simpler to treat. For example, in a project injecting 1 million tonnes/yr of CO₂, a significant impact might be framed as a well leaking at 0.1% of the injection rate (i.e., 10,000 tonnes/year; cf., IPCC’s target of > 99% storage performance over 1,000 years, Metz et al., 2005). This corresponds to the FutureGen high leak-rate case.

Table 2 shows values for an example calculation to translate effective permeabilities into leak rates using the Darcy equation. This example illustrates that very high effective permeabilities are required to reach highly impacting leakage scenarios. The estimated permeabilities are of the order 100–500 D depending on details of the leakage path, depth, etc. The largest effective permeability determined from SCP data by Tao et al. (2010a) was of order 0.1 D. Thus, the highly impacting rates utilized by FutureGen are not present in SCP data. These are in fact closer to blowouts and the FutureGen risk assessment assumed that such leak rates would be easily detected and therefore fixed in just over a month (This may be an optimistic assumption given recent experience with the Macondo Gulf of Mexico blowout and the Aliso Canyon, California, methane leak.)

Where do the chief risks lie in wellbore leakage? There appear to be three distinct scenarios of greatest concern.

- 1) Abandoned wells that are not plugged and therefore open to unrestricted flow. The potential leak rates for these wells are being researched in other NRAP activities (see Pan et al., 2011). The likelihood of such wells is non-existent in regions without existing wells, but could be finite in regions with a significant number of very old (pre-1950) wells. Aeromagnetic surveys can help find these old (buried) wells and reduce risk (Hammack et al., 2006).
- 2) Wells with defective seals (either in the external annulus or the internal plug) leaking at slow to moderate rates. This category is covered in this report with six example frequency distributions illustrated in Figures 8–11. The potential impacts of gas migration from such leaks is perhaps most significant to the environment. Here the slow accumulation of CO₂ could result in deteriorated water quality (e.g., Keating et al., 2013) or damaged ecosystems (e.g., Farrar et al., 2002). These leaks can also impact carbon storage accounting if a sufficiently large number of wells leak over a

long period of time. Note however, that the largest calculated CO₂ leak rate from SCP data was only about 15 tonnes/year (Tao et al., 2010b) suggesting that significant problems would require a significant number of such defective wells.

- 3) Underground blowouts induced by sustained casing pressure. As discussed by Bourgoyne et al. (2000), in worst case scenarios SCP can lead to a pressure build-up large enough to burst casing. This could result in very high flow rates and could potentially damage surface structures. These events are not captured in this report and require further investigation. For example, it is unlikely, and unclear, whether this scenario could apply to abandoned wells.

Of these three scenarios, gas migration by processes similar to that captured in sustained casing pressure data (Scenario 2) is the most likely event for a sequestration project. This preliminary work suggests that such gas migration problems pose the greatest potential risk of leakage for sequestration projects containing a significant number of old and/or abandoned wells.

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NRAP is an initiative within DOE's Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO₂). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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